# Buckling and Postbuckling Studies on Stiffened Composite Panels with Circular Cutouts

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ABSTRACT

*An analytical study has been carried out to investigate the buckling behaviour of rectangular composite stiffened panels with circular cutouts. The effect of parameters such as cutout size, inclination of cutout flange, location of stringer with respect to the cutout and stringer height on the buckling and postbuckling performance has been studied through non-linear FE analysis. The study has helped to develop a few guidelines in the preliminary design stage of composite wing panels.*

Keywords: Buckling, Postbuckling, Stiffened panels, Cutout, First ply failure

## 1. Introduction

Advanced composites are finding extensive applications in primary structures like wing, fin etc. of military and civil aircraft due to their excellent properties. In a typical wing structure the skin panels are subjected to in-plane stresses under various load conditions. Under compressive and shear loads, the buckling behaviour of the panels becomes a driving factor for design. Often the panels have high reserve strength beyond buckling, which can be exploited to achieve efficient structures. Hence, buckling and postbuckling studies of composite panels have received much attention over the years.

In a wing structure the skins contribute a major portion of the weight of the structure. In order to keep the thickness of the skin to a minimum, stiffened construction is adopted. Stringers are provided as stiffeners in the inter-spar (I/S) box of a typical transport aircraft in the primary bending direction to adequately stiffen the skin against buckling. The spacing and the geometry of the stringers are important design parameters. Cutouts in wing skin are provided for accessing and maintaining fuel tanks and systems. The cutout parameters such as shape, size, its location with respect to the stringers etc. are decided to achieve enough stiffness of the panel and to avoid much weight penalty. The effect of the cutout parameters must be known to arrive at an efficient design.

Extensive literature, both the experimental and analytical, is available on the buckling and postbuckling behaviour of laminated composite plates and shells. Most of the literature is available for square plates. Ref. 1, 2 and 3 are buckling studies on square plates with circular cutouts. The buckling loads are studied for various cutout sizes. They showed that some orientations of the lay-ups with values of d/b > 0.35, the panel critical buckling load in square plates is increasing with increasing cutout size and even in some cases, the critical buckling load is much more higher than that for a panel without any cutout. Ref. 4 studied the FE modeling aspects of stiffened panels. Ref. 5 studied the postbuckling behaviour of graphite-epoxy laminated stiffened panels analytically and experimentally. In this research, the stiffened panels were analyzed using the nonlinear finite element method. The postbuckling compressive strengths of the hat stiffened panels were five to seven times higher than the buckling load for the I stiffened panels.

There are not sufficient guidelines available in the open literature on the buckling and postbuckling behaviour of stiffened composite panels that can be readily used in the design. An experimental programme to study the behaviour of stiffened panels with cutouts for buckling and postbuckling is time consuming and costly. In such a case an analytical modelling with FEM is considered an alternative. The FEM gives considerable flexibility to model various configurations. In the present work this approach is adopted. The buckling and postbuckling behaviour of skin panels has been studied under linear and nonlinear FE analysis for a few important parameters. In this study, the buckling behaviour of only rectangular panels under compressive loading has been considered. The study has resulted in some guidelines for the preliminary design.

## 2. FE Model Description

The finite element modeling and analysis have been done using HyperMesh pre/post processor and MSC/NASTRAN respectively. The two dimensional shell elements CQUAD4 and CTRIA3 are used for the analysis. These elements support large deformations based on the nonlinear analysis [6]. The MAT1 and MAT8 Bulk data entries of NASTRAN are used to specify the isotropic and orthotropic (for composites) material properties respectively. The principle material direction is in the applied force direction.

### 2.1. Loads and boundary conditions

A typical skin panel surrounded by two ribs and two stringers of an aircraft wing is shown in Figure 1(a). It is difficult to simulate the actual boundary conditions of the panel in the FE analysis. Therefore, the panel is considered as simply

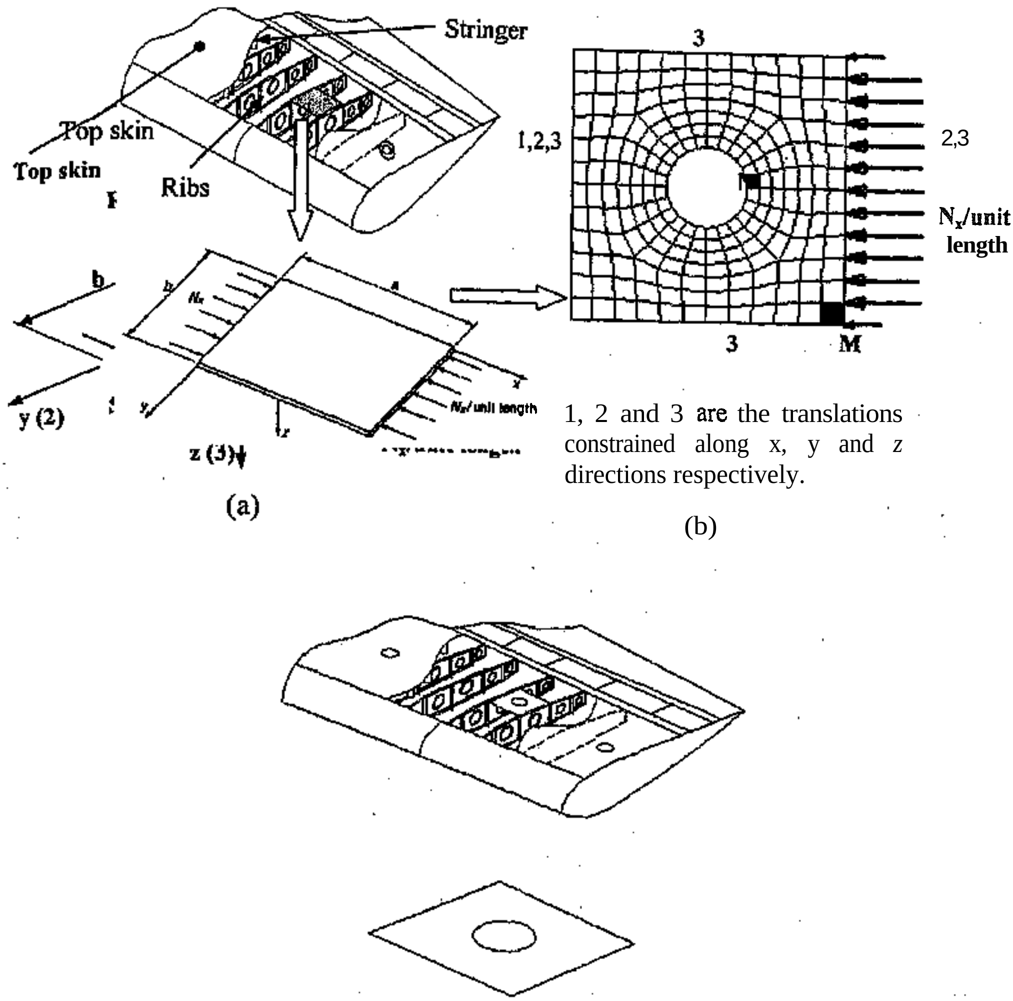



**Figure** 1. Loads and boundary conditions (a) Panel under consideration (b) FE model of skin panel

supported along the two unloaded edges, where the stringers are located. The loaded edges are normally bolted or co-cured with the ribs. These edges are also considered as simply supported, but constrained the movement along the rib (i.e. translation along 2). Figure 1(b) shows the FE model of the skin panel along with the boundary conditions. In the FE model the axial force ($N_x$) is applied on one edge and on the opposite edge the translation along 1 is constrained to simulate the symmetric uniaxial loading condition. From a convergence study it has been found that a minimum 12 elements are required at each edge of the panel.

## 2.2. Material Properties

The properties of the unidirectional carbon fiber composite and foam materials considered for the study are given below.

Composite: $E_{11}$ = 117 GPa, $E_{22}$ = 9 GPa, $\upsilon_{12}$ = 035 and $G_{12}$ = 4.5 Gpa

XT = 388 MPa, $X_C$ = 453 MPa, $Y_T$ = 22.5 MPa, $Y_C$ = 22.5 Mpa

and S = 32 Mpa, The thickness of each layer = 0.16 mm

Foam: E = 0.18 GPa and $\upsilon$ = 0.2817

## 3. Validation with previous work

In order to validate the prediction of postbuckling strength using NASTRAN in the present study a typical stiffened composite panel for which experimental and analytical results [5] are available, is considered. A non-linear analysis carried out in NASTRAN and the results are compared (Figure 2) with that in Ref. 5. The difference between the buckling loads ($P_{cr}$) from the NASTRAN and the experiment is only 2%. In order to get the failure load ($P_{crF}$) the first ply failure is computed based on the maximum strain criterion. The failure load obtained from the experiment shows a difference of 8% with the first ply failure load computed in the present study. The end shortening of the panel for the variation of the load from the two results shows quite close correlation. In Figure 2, the buckling mode at point 'A' obtained from both previous work and the present analysis is also shown. The NASTRAN results are in good agreement with the previous work.

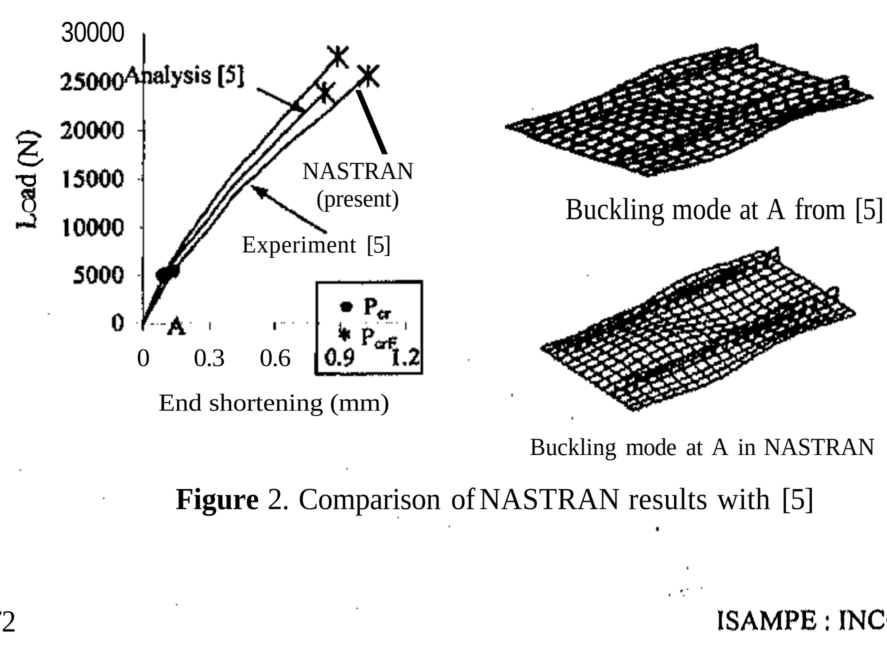



**Figure** 2. Comparison of NASTRAN results with [5]

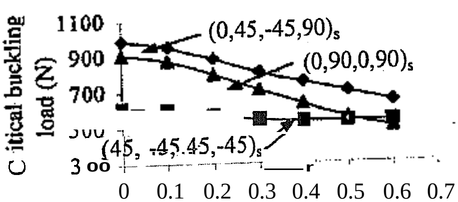
## 4. Results and Discussion

The above procedure of postbuckling analysis using NASTRAN has been carried out to study the effect of a few parameters on the buckling and the postbuckling performance of skin panels. The parameters considered here are cutout size, flanged cutout and distance of stringer from the center of cutout and stringer height.

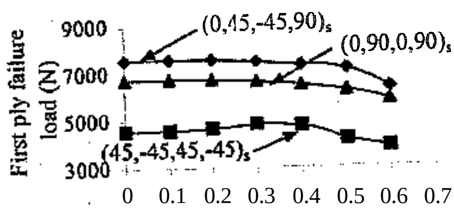
### 4.1. Cutout size in rectangular panels

The buckling behaviour of the compression loaded rectangular panels with a central circular cutout is studied. The cutout diameter to panel width ratio (d/b) is increased from 0 to 0.6 in order to find the effect of the increasing cutout size. The lay-up sequence considered are $(0/+45/-45/-90)_s$, $(0/90/0/90)_s$ and $(+45/-45/+45/-45)_s$ all of 1.28 mm thick. In order to see the effect of increased thickness of laminate on the buckling behaviour 2.56 mm thick another set of laminates with lay-up sequences $([0/+45/-45/-90]_2)_s$, $([0/90/0/90]_2)_s$ and $([45/-45/45/-45]_2)_s$ are considered.

The results from the study show a trend of monotonic reduction in buckling load with increasing cutout size for lay-ups $(0/+45/-45/-90)_s$ and $(0/90/0/90)_s$ as shown in Figure 3(a). However, the $(+45/-45/+45/-45)_s$ lay-up shows only marginal reduction in the buckling load as the d/b ratio increases. For smaller cutouts the load path is centrally located and in this cases 0 and 90 are effective in providing stiffness to the panel. As the d/b ratio increases the load path is deflected towards the unloaded edges because of the central cutout. In this case the presence of angle plies (45 and −45) helps to stiffen the panel. The Figure 3(b) shows that ail the panels have failure load substantially greater than their buckling load.




(a)




(b)

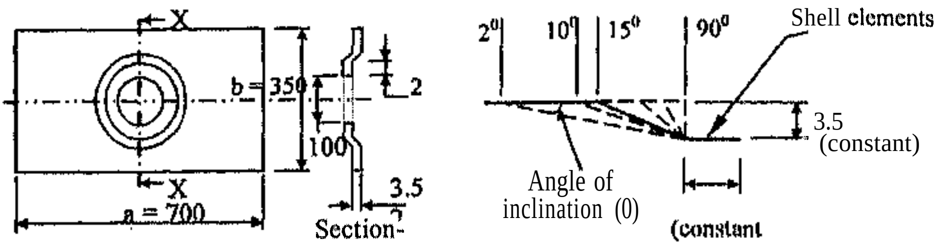
**Figure 3.** Critical loads for various d/b ratios (a) Buckling loads (b) First ply failure loads

For all the values of d/b < 0.5 the first ply failure is at the loaded edge (point M) of the panel, but for d/b > 0.6 the first ply failure is at the edge (point N) of cutout as shown in Figure 1(b). For d/b > 0.4 the postbuckling strength is decreasing rapidly. Therefore, in the case of rectangular panels it is preferable to adopt cutouts of d/b

<0 4 The buckling behaviour of composite panels with thickness 2.56 mm is quite same as that of thickness 1.28 mm and therefore, not presented here.

## 4.2. **Angle of** flange of cutouts

Flanged cutouts are provided on the skin of an aircraft wing as a seating for the access cover. The flange around the cutout also helps in stiffeneing the cutout area. Figure 4(a) shows the geometry of a typical flanged cutout. The lay-up considered is (45 -45 0 45 90, -45, 0, 45, 0, -45, 90)$_s$. The flat portion around the cutout is kept constant (20 mm) as shown in Figure 4(b). The angle of inclination (0) of the flange around the flat portion of the cutout is varied from 2° to 90 . The buckling load ($P_{cr}$) and the first ply failure loads ($P_{crF}$) are computed from the analysis. The loads are applied on the edge 'a' of the panel.




(a) (b)

Figure 4. Typical geometry of the panel (a) Panel with flanged cutout (b) Variation of the angle in the flanged cutout

Figure 5 shows the buckling load and the first ply feilure for various angles (0) of the flanged cutout. For all the angles of flange the buckling load is higher than that of a panel with a plain cutout (no flange case). This is true for even low angles (0 ~ 2°). However, manufacturing of the access covers with very small angle is not feasible because of sharp edges. The increase in the angle reduces the buckling load till 15° and thereafter the buckling load is constant till the angle becomes 90 , The failure load ($P_{crF}$) computed shows marginal increase from a low angle of inclination to an inclination of $15^0$ and thereafter the load remains constant up to 90°. Therefore, $15^0$ inclination can be adopted for configuring the flange around the cutout, This value is feasible as far as the ease of fabrication also concerned.

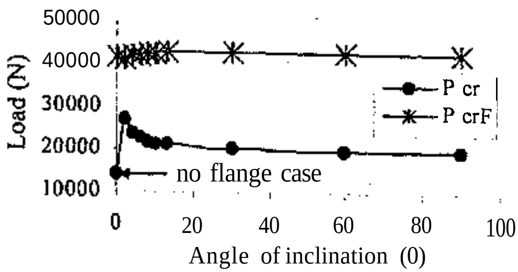



Figure 5. Buckling and first ply failure loads in a panel with flanged cutout

### 4.3. Stringer distance

The effect of location of the stringer on a rectangular panel with a centrally located circular cutout is studied. The study is done for cutout with and without flange. Two stringers are provided on both sides of the circular cutout. The load is applied along the length 'a'. The stringers are located in the direction of the force as shown in Figure 6(a). The d/b ratio is kept 100/350 = 0.28 for this study. Figure 6(b) shows the section of the stringer that has a core made of foam. The lay-ups for the panel and the stringer are (45, -45, 0, 45, 90, -45, 0, 45, 0, -45, 90)s and (45, -45, 0, 90)s respectively. The stringer distance is varied from 100 mm to 325 mm. The end shortening (at y1) of the loaded edge and the lateral displacement at the edge of cutout (at z2) are computed for the study.

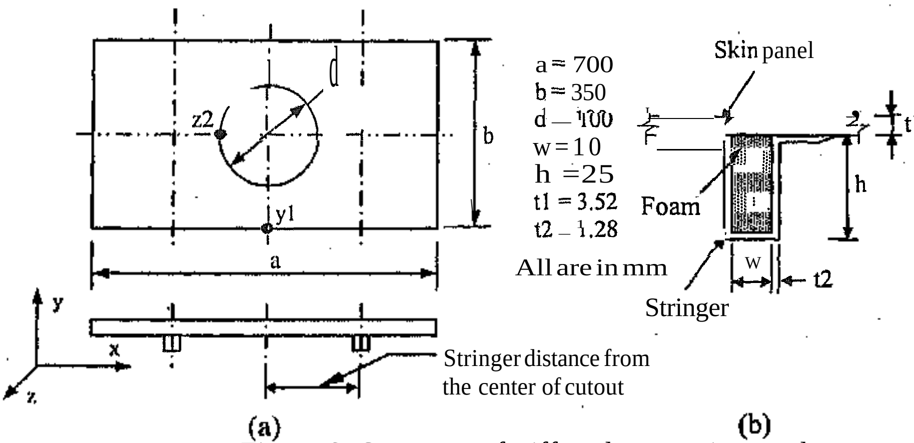



Figure 6. Geometry of stiffened composite panel

The end shortening and the lateral displacements are shown separately for various stringer distances from the center of cutout (no flange case) in Figure 7. From Figures 7(a) and 7(b) it can be seen that when the stringer distance is 125mm the panel shows the highest buckling load and the highest first ply failure load. The end shortening and lateral displacement computed for higher stringer distances are much higher than that when the stringer distance is 125 mm. Such higher lateral displacements may not be acceptable due to aerodynamic considerations. Figure 8(a) shows that when the stringer distance is 125 mm the buckling load and the failure load are quite close. This also gives an indication that for the present configuration of the panel a stringer distance of 125 mm is quite suitable. Figure 8(b) shows the buckling and failure load when a flanged cutout (0 = $15^{0}$) is considered. In this case the highest buckling load is observed when the stringer distance is 150 mm. The difference between the buckling load and the failure load has come down in general.

In all the cases the failure is near the end of the stringer on the skin panel as shown in Figure 9. In all the above cases the first ply failure is transverse to the loading direction in the first layer close to the stringer.

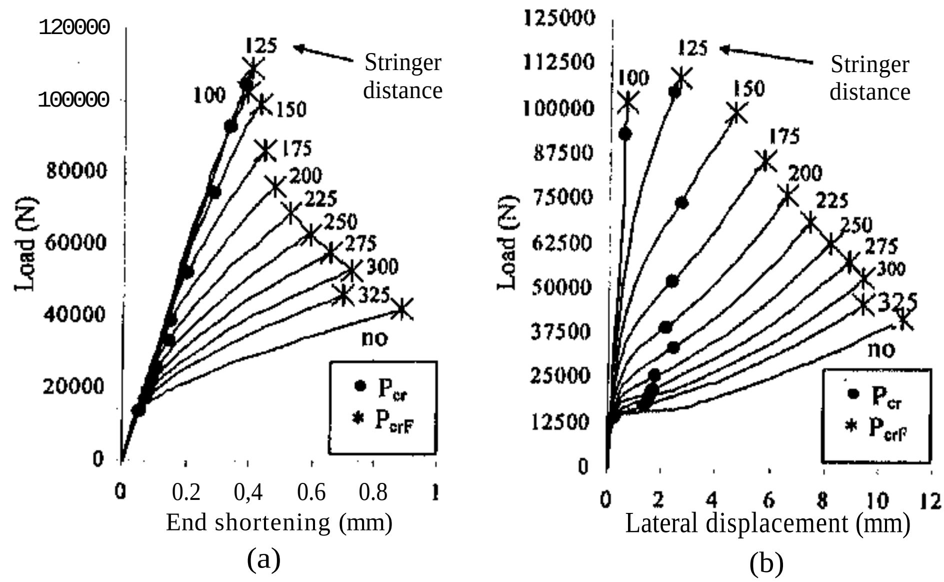



**Figure** 7, Load - Displacement curves (a) End shortening (at y 1)
(b) Lateral displacement (at z2)

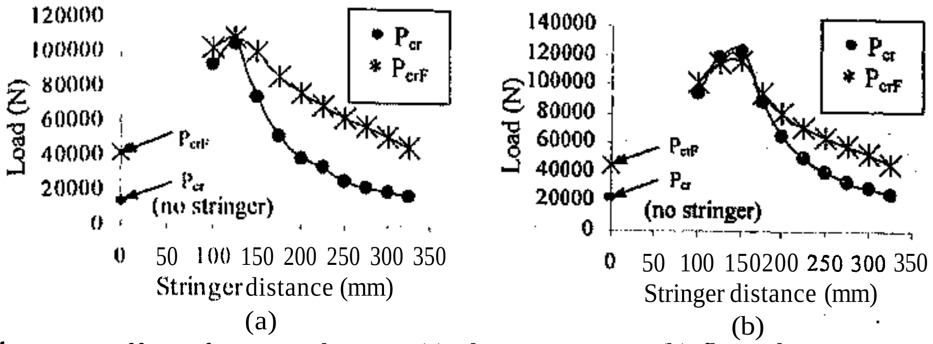



**Figure** 8. Effect of stringer distance (a) plain cutout case (b) flanged cutout case

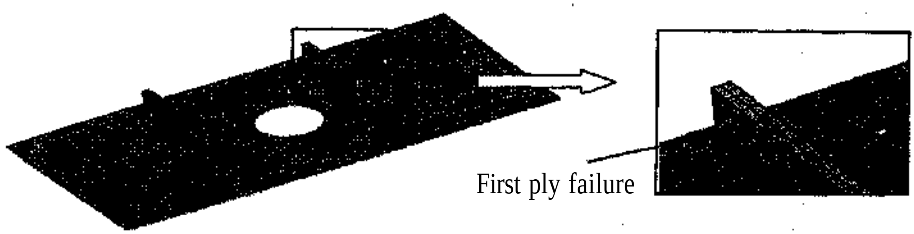



**Figure** 9, Location of First ply failure

## 4.4. Stringer height

In order to study the effect of stringer height on the buckling behaviour, the height of the stringers in the panel considered in Section 4.3 has been varied from 15 mm to 30 mm. The stringer distance is kept constant at 125mm while varying the stringer height. The stringer height is increased in steps of 2.5 mm. The other parameters kept same as in Section 4.3. Figure 10 shows the buckling load and the first ply failure load for various stringer heights. The buckling load ($P_{cr}$) increases steadily from a stringer height of 15 mm to height of 20 mm and thereafter the buckling load remains same. The failure loads ($P_{crF}$) show lower values than the buckling load up to a stringer height of 20 mm and thereafter show slightly higher values than the buckling load. From the result it is concluded that a stringer height of 22.5 mm is quite suitable for this configuration and stringer heights above 22.5 mm do not really improve the buckling performance of the panel.

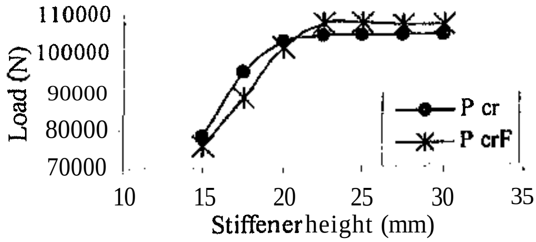



Figure 10. Effect of stringer height

The location of first ply failure is on the stringer for stringer heights below 22.5 mm and for higher stringer heights the failure occurs at the edge of the stringer on the skin panel as in Figure 9.

## 5. Concluding remarks

An analytical study using NASTRAN has been carried out to study the buckling behaviour of rectangular composite stiffened panels with circular cutouts. The effect of a few parameters on the buckling and postbuckling performance has been studied through non-linear FE analysis. The study has helped to develop a few guidelines in the preliminary design stage of wing panels. The results have showed that in many cases the panels are capable of carrying loads substantially greater than their buckling loads. However, the magnitude of out-of-plane displacements may become the limiting criterion in the design of structures operating in the postbuckling region. Following conclusions have been drawn from the study.

1. In the case of rectangular panels with circular cutouts there is a monotonic reduction in buckling load with increasing cutout size for typical lay-ups
2. There is no substantial reduction in the postbuckling strength of the panels up to a d/b ratio of 0.4. Therefore, the d/b ratio $<$ 0.4 can be adopted.
3. Flanged cutouts provide higher stiffness around the cutout and therefore, help in improved buckling performance of the panel. The present study has showed that an inclination of 15° for the flange is suitable for an acceptable buckling performance and fabrication ease.
4. The buckling performance of the panel can be increased by suitably locating the stringers in the panel. A stringer distance of 125 mm and 150 mm can be adopted for panels with plain cutout and flanged cutout respectively for the panel configurations considered here.
5. The buckling load and postbuckling strength increases with the increase of the stringer height up to a certain limit and thereafter there is no effect of the stringer height. For the panel configurations studied here a stringer height of 22.5 mm is acceptable.

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